Consolidating Achievable Science with SmallSats/CubeSats

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Motivation

Cubesat = 4 to 25 kg (3U to 12U)

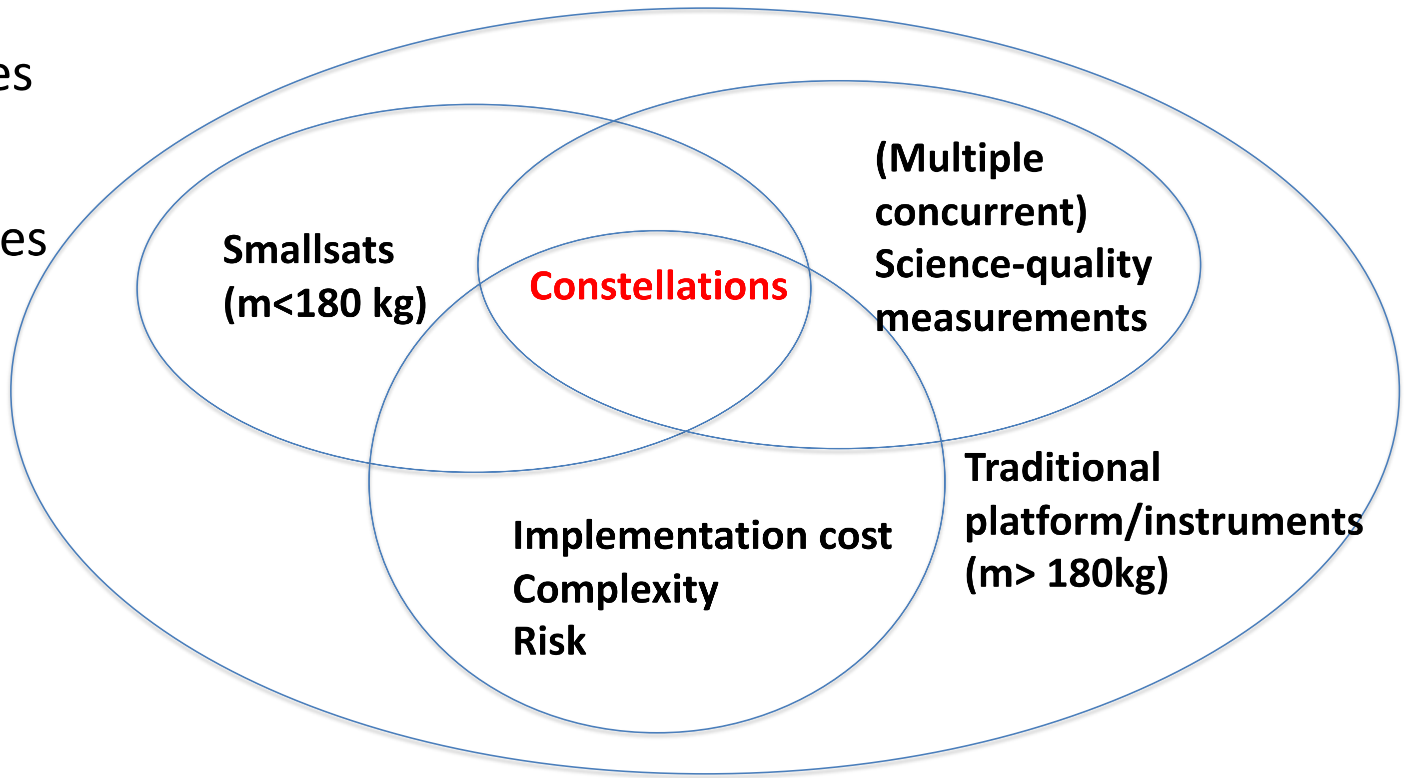
ESPA-compatible smallSat = 25 to 180 kg

SmallSats/CubeSats show capability of science quality* measurements enabled by:

- Significant instrument miniaturization advances
- Advances in small spacecraft buses
- Flexibility in launch and deployment approaches
- Creativity in mission architecture design
- End-to-End affordability

Focus on Science:

- New scientific observations are possible, via constellations, formation flying, and sensor disaggregation



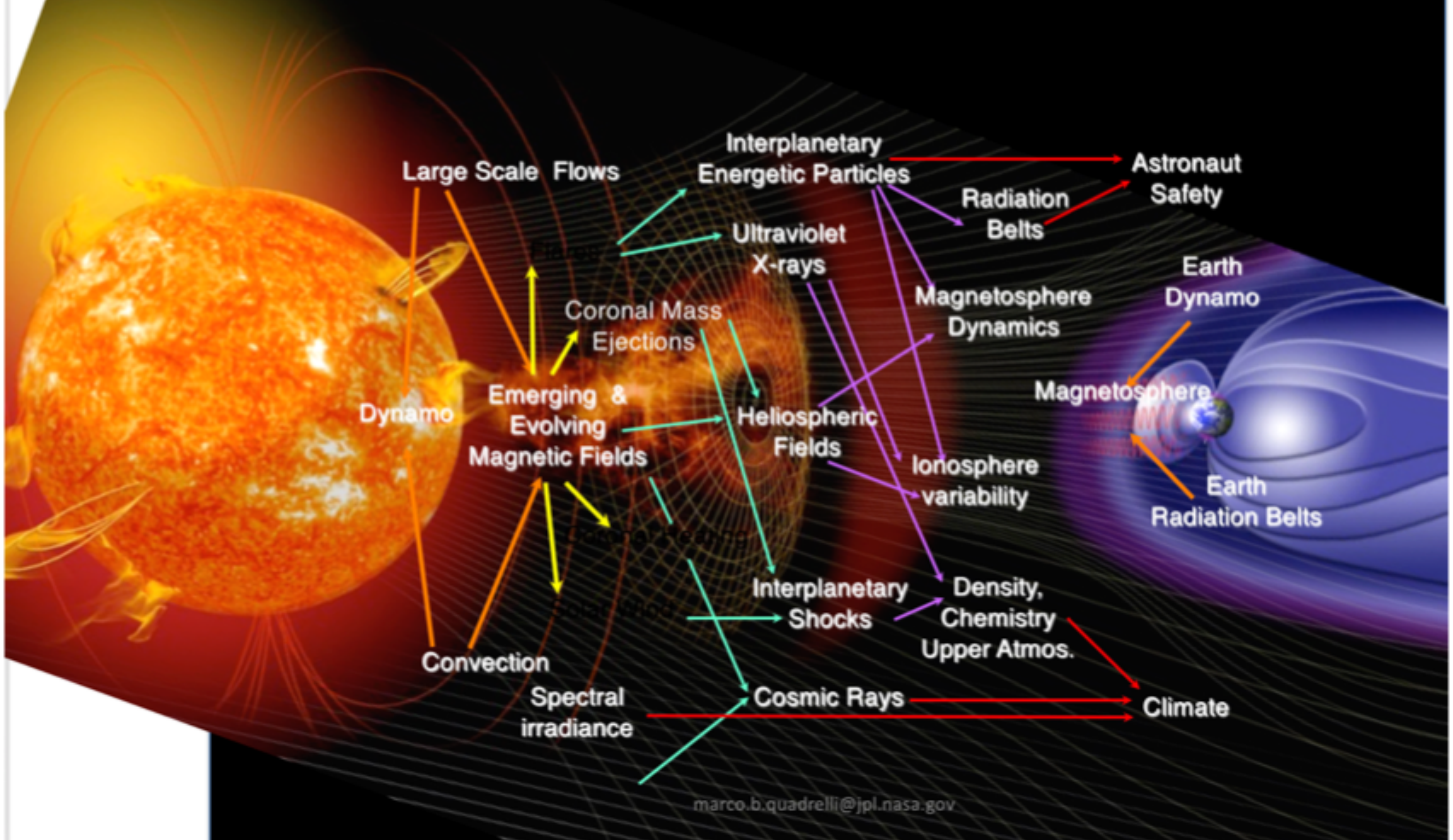
This talk discusses the value added to planetary science, heliophysics, earth science, and astrophysics **measurements** by single smallsats and constellations

*Equivalent to that of traditional instrument/platform or degraded but still acceptable

Systems of distributed CubeSat/SmallSats are game-changers

- New scientific observations are possible, **specifically exploiting the concepts of constellation or formation**
- Advantages of constellations:
  - Topologies: Possibility of distributed and heterogeneous measurements
    - Sensor heterogeneity → Multiple types of spectrometers, Spectrometer + imager, Organics in-situ sampler + fields
    - Heterogeneous constellations → Different revisit times on different orbits, Large data volumes, DSN/TDRSS/GPS involved
    - Lower altitude (stratospheric, suborbital) + higher (LEO, GEO) → would enable a sensor web across multiple domains
  - Density: Possibility of increased density and spatio-temporal resolution with constellations (CYGNSS)
    - Higher temporal resolution and spatial sampling → require critical orbit coverage
    - Increased robustness → leads to graceful degradation with large numbers of low-cost detectors
  - Precision: Possibility of more precise timing/ranging with formations
    - Achieving high ground resolution → requires tight relative pointing & control
    - Enabling high levels of instrument synthesis → requires multiple baseline interferometry
    - Leveraging precise clock, ranging → leads to costly sensor calibrations
    - Availability of increased autonomy → enables agile retargeting, repointing, reconfiguration
  - Leverages increasing availability of small instruments

A Complex, Coupled System



Science case for Heliophysics

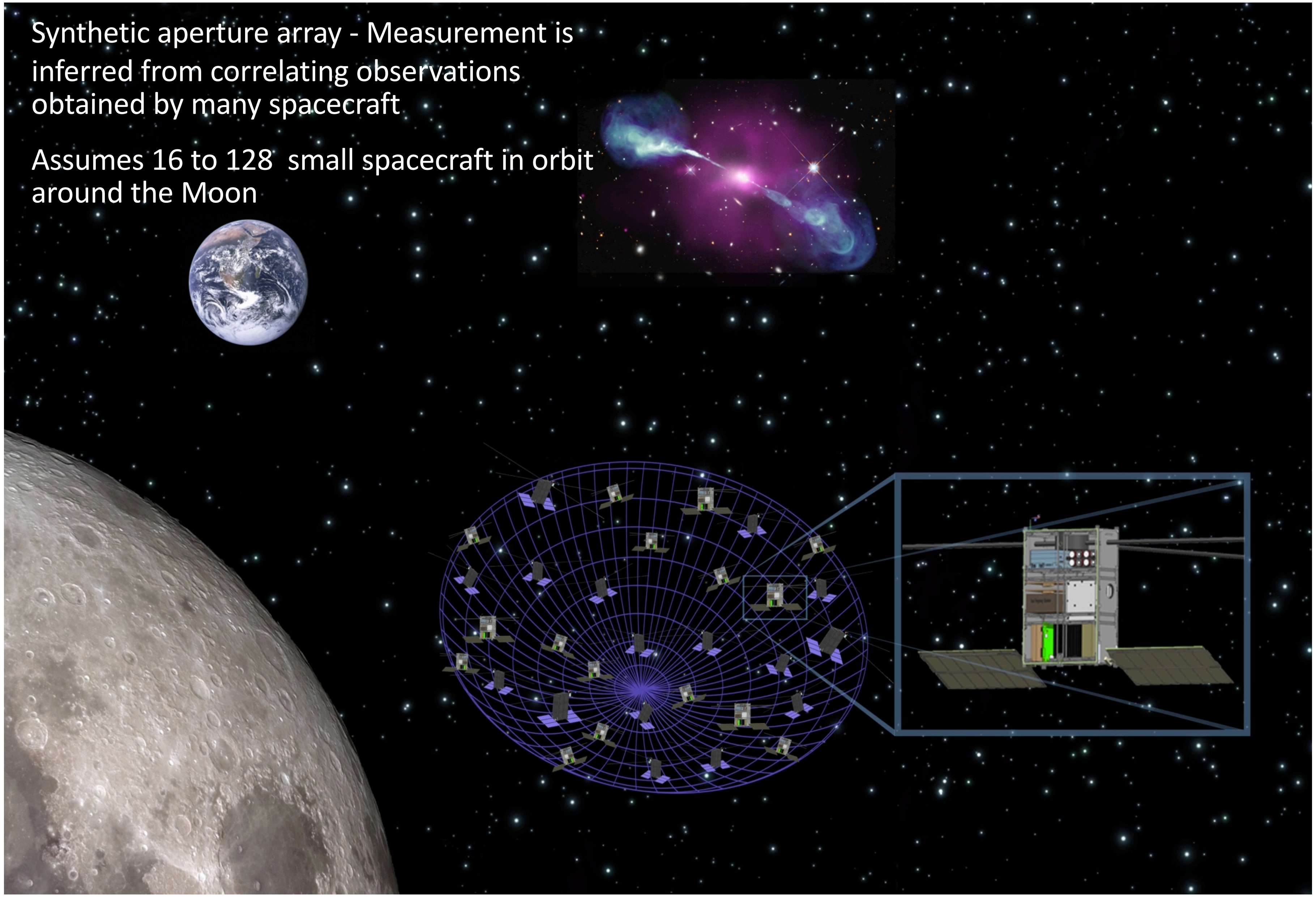
Measurement(s)	SmallSat candidate?
Boundary and solar wind plasma measurements Energetic neutral atoms Direct samples of interstellar matter and solar wind, magnetic field, suprathermal ions	Yes
Wind velocity and temperature between 80 and 300 km Far UV imager for species altitude profiles and ditributions Ion and neutral wind velocity and mass spectrography	Yes
Image plasmasheet and ring current energetic neutral atoms Evolution of plasma density via EUV imaging. Near Earth FUV emissions In situ ion and electron plasma densities, temperatures, velocities to 30 keV, and in-situ magnetic fields.	Yes
Use 6 identical Satellites occupying 30 deg separated orbital planes in 450 km circular orbits Measure neutral and ion velocities, temperature, densities, composition, vector magnetic fields, electron distribution between 0.05 eV and 20 keV	Yes
Tomographic images of plasma density in magnetotail, flank, and subsolar magnetosphere 3-axis flux magnetometer Electrostatic analyzers Radio tomography instrument	Yes
3-axis magnetic fields 3D ion-electron plasma analyzer Energetic ion-electron particle telescope	Yes

- Capturing **coupled** phenomena in heliophysics require multi-point (and often multi-orbit) in-situ and remote-sensing measurements in key regions in the Sun-Earth domain, which naturally lead to large constellations

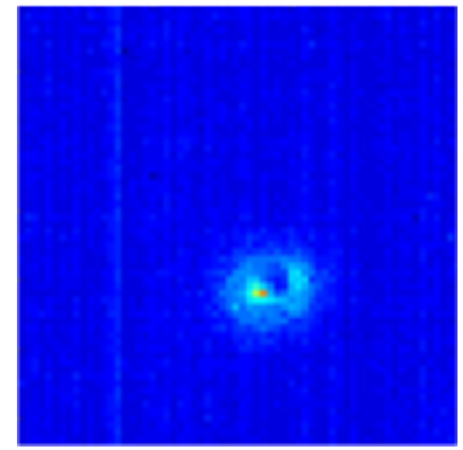
Science Area	Smallsat-enabled mission concept for LWS program
Solar outputs	• Stereoscopic EUV imaging • Magnetography well off the Sun-Earth line
Ionospheric inputs	• A solar wind constellation that observes from ~ 30 RE upstream • An ionospheric constellation to drive coupled magnetospheric-ionospheric models
Satellite drag and thermospheric density	• Fleet of 12U–27U 3-axis stabilized smallsats
Plasmaspheric plasma irregularities	• Active direct measurement (VHF-UHF Radio) of TEC • Passive indirect measurements (UV) of TEC
TEC and scintillation	• Active direct measurement (VHF-UHF Radio) of TEC • Passive indirect measurements (UV) of TEC
Solar energetic particles	• Low-frequency Imaging Array in Space

LWS = Living With a Star

Radio-Galaxies Imaging with RELIC



ASTERIA



- ASTERIA achieved (2017) 0.5 arcsecond-level line of sight pointing error and highly stable (<0.01K) focal plane temperature control.

Science cases for Astrophysics

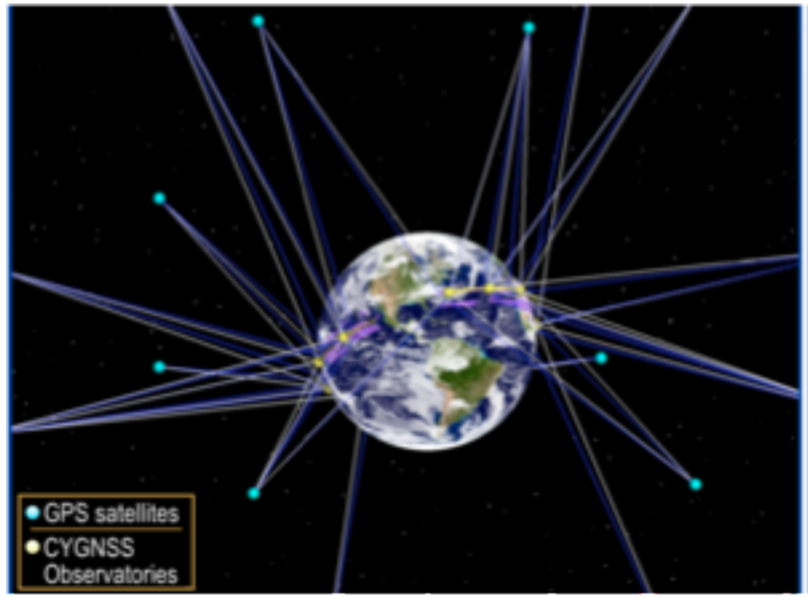
Measurement(s)	SmallSat candidate?
detect compact stellar remnant binaries comprised of white dwarfs, neutron stars and black holes	Yes
physics of cosmic inflation	Possibly
directly image forming protoplanetary condensations in new planetary systems	Possibly
Relation between galaxy growth and black holes. Reionization in the early universe, through high-spatial-resolution imaging and moderate-to-high-spectral-resolution spectroscopy of the first galaxies and quasars	Yes
spin distribution of black holes in the local universe	No
Spin distribution of black holes. Imaging the accretion disks of nearby feeding black hole	Possibly
2-20m signals to study very high redshift 20cm line – array of thousands of radio antennas on the far side of the moon –3D map of neutral gas from EoR to deep into the dark ages.	Yes
Xray interferometer with (sub)microarcsec resolution to image black hole event horizon.	No

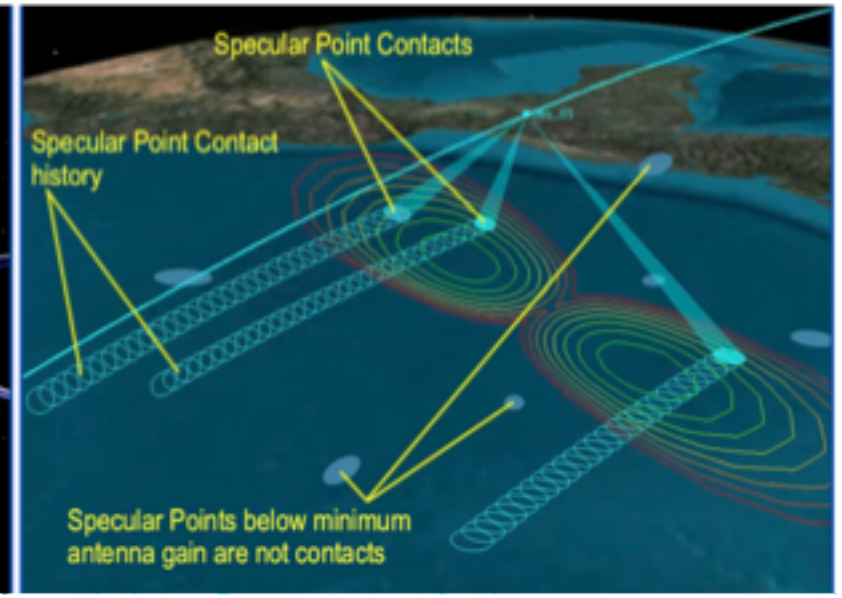
Opportunities for Smallsats are limited:

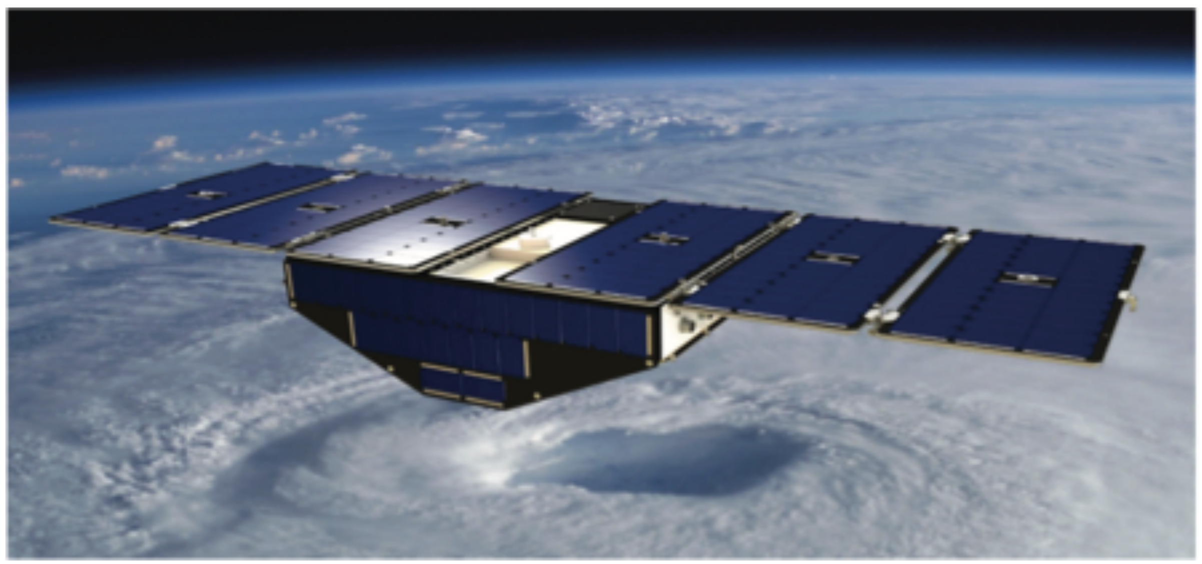
- Discipline dominated by need for photons
- Exoplanets are very faint, long exposure times, time domain observations
- Up to now, only identified opportunities for CubeSats are interferometry in radio, eventually in optical (far out)
- Time Domain Astronomy UV for high energy transient events
- These technologies will enable precision photometry, i.e. the careful measurement of stellar brightness over time in future CubeSat constellations.

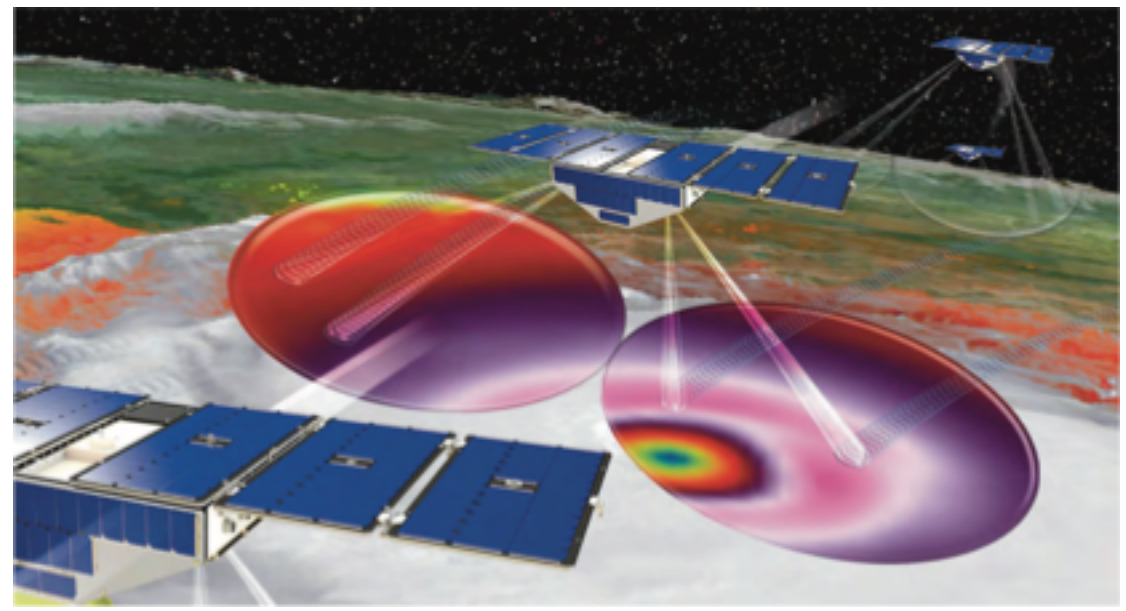
CYGNSS as an example of smallsat constellation for earth science

- Univ. of Michigan led
- Example of sensor disaggregation: GPS transmitter and reflection receiver form a bi-static radar pair
- Non-traditional sampling of wind fields to yield sea-surface wind speeds
- Community still evaluating data product characteristics





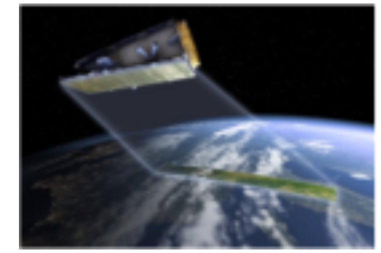


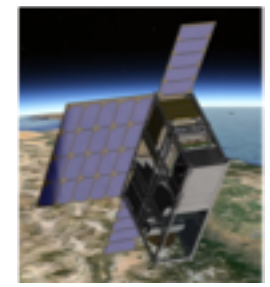


Science Cases for Earth Science – ESAS-2017 Designated and Explorer

Target Observable	Candidate Measurement Approach	SmallSat Potential
Aerosols	Backscatter Lidar and Multichannel/Multiangle polarization imaging radiometer (same platform)	Yes: ESPA-Class on same platform or constellation on separate platforms. Lidar technology needed.
Clouds, Convection, & Precipitation	Radar(s) with multi-frequency passive microwave and sub-mm radiometer	Yes: ESPA/CubeSat constellations. Deployable aperture antenna technology needed.
Mass Change	Spacecraft ranging measurement of gravity anomaly	Near-Term: ESPA-Class constellations. Laser-ranging, targeting, spacecraft stability needed.
Surface Biology & Geology	Hyperspectral imagery (visible, SWIR), Multi/Hyperspectral imagery in the thermal IR	Yes: ESPA-Class constellations on same or multiple platforms.
Surface Deformation & Change	Interferometric Synthetic Aperture Radar (InSAR) with ionospheric correction	Yes: ESPA-Class constellations. On-board processing, large deployable apertures, formation flying needed.
Greenhouse Gases	Multispectral short wave IR and thermal IR sounders or Lidar	Yes: ESPA-Class or MiniSat constellation for SWIR and Thermal IR. Lidar technology needed.
Ice Elevation	Lidar	Long-Term: Lidar technology needed.
Ocean Surface Winds and Currents	Radar scatterometer	Near-Term: ESPA-Class or MiniSat constellation.
Ozone and Trace Gases	UV/IR/microwave limb/Nadar sounding and UV/IR solar/stellar occultation	Near-Term: ESPA-Class to CubeSat constellations. Spectrometer development needed.
Snow Depth and Snow Water Equivalent	Radar (Ka/Ku band) altimeter or Lidar	Near-Term (as a spectrometer). Long-Term as Ka/Ku Radar or Lidar in ESPA-Class constellation.
Terrestrial Ecosystem Structure	Lidar	Long-Term: Lidar technology needed.

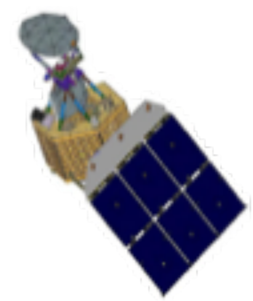
Surface Deformation & Change
NovaSAR-S Small Satellite Synthetic Aperture Radar Platform
Surrey Satellite Technology SSTL





Snow Depth & Snow Water Equivalent
Snow and Water Imaging Spectrometer (SWIS)
Jet Propulsion Laboratory

Aerosols
Hyperangular Rainbow Polarimeter (HARP)
Univ. of Maryland Baltimore County

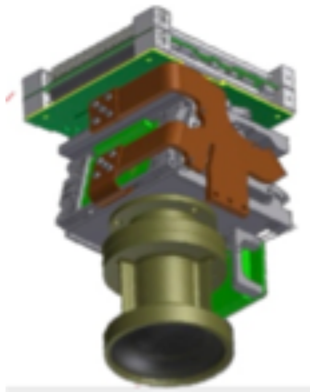


Ocean Surface Winds & Currents
Compact Ocean Wind Vector Radiometer (COWVR)
USAF/ORS and Jet Propulsion Laboratory

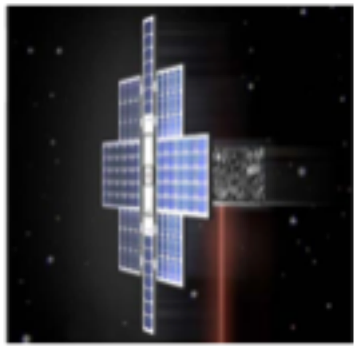
Science case for Planetary Science

Science themes	Measurement categories	Potential for distributed measurements using constellations
Building New Worlds	Tunable laser Spectrometer (TLS)	Multi probes in Venus, Mars and giant planet atmosphere
Building New Worlds	Quadrupole Ion Trap spectrometer (QITMS)	Multi probes in Venus, Mars, and giant planet atmosphere
Building New Worlds	Magnetometers	Additional mag sensors on Psyche, missions to the Moon
Planetary Habitats	Thermal IR imager, Bolometer (SoA, 10-100 micron), Thermopile array (10-26 micron)	Combination of detectors at multiple vantage points (orbiter + landers)
Planetary Habitats	Quadrupole Ion Trap spectrometer (QITMS)	Not evident science driver for targets of interest (Europa/Enceladus plumes)
Planetary Habitats	Magnetometers Energetic particle spectrometer	Distributed sensors at icy moons (especially Europa)
Solar System Workings	Thermal IR imager, Bolometer (SoA, 10-100 micron), Thermopile array (10-26 micron)	Combination of detectors at multiple vantage points (orbiter + landers)
Solar System Workings	Magnetometers Energetic particle spectrometer	Distributed sensors for giant planets, Europa, Venus

HARP Imaging Polarimeter (3U)
UMBC/SDL (2017)

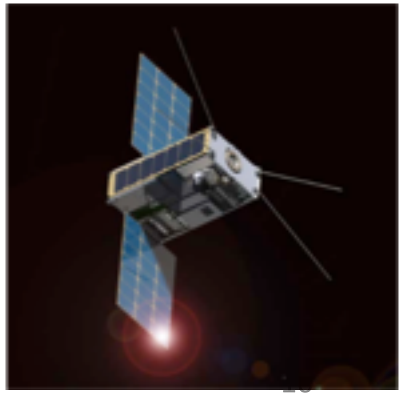


Lunar Flashlight NIR Laser (6U) MSFC/JPL (2017)



Mass Spectrometer (3U)
JPL (TBD)

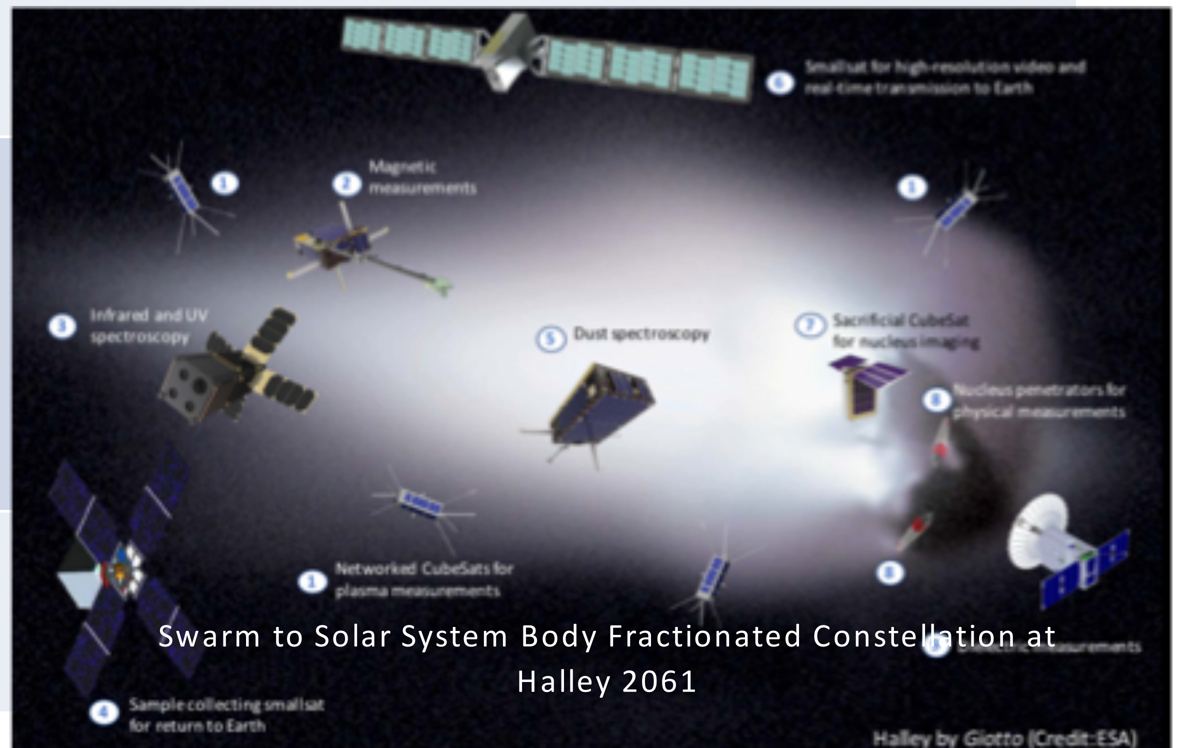
LunarIceCube IR Spectrometer (6U)
GSFC (2018)



- In planetary science at least, the big contribution of CubeSats/smallsats is to provide access to targets that are not necessarily high on NASA's priority list.
- Many targets can be explored within the constraints of the SIMPLEx program ($55M, secondaries on Discovery launches).
- Specific topics that are of interest to the community but don't necessarily have a place in the decadal survey can also be approached with CubeSats/smallsats, e.g., NEO reconnaissance for in situ resource assessment.

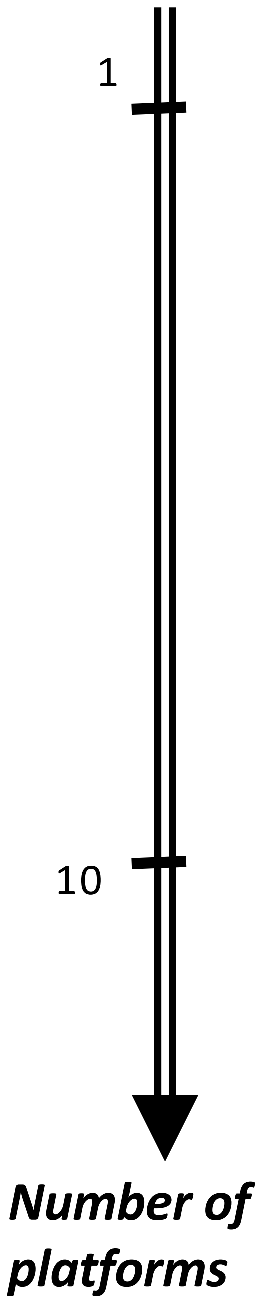
SmallSats constellations enable new types of measurements

Domain	Constellation type
Planetary Science	• Multiple TLS/QITMS spectrometers would collect and analyze elements at separate spatial locations and different times if on different orbits. • Multiple thermal imaging spectrometers would provide thermal data at separate spatial locations and different times if on different orbits. • Multiple Doppler imagers at separate spatial locations and different times on different orbits. • Constellations will be useful to sample magnetic and plasma field at multiple locations. Would need >10 Cubesats. Sampling of many bodies within a population. • CubeSats distributed across the rings of Saturn. • SmallSats sampling multiple comets as part of the same mission
Heliophysics	• Stereoscopic EUV imaging. • Magnetography well off the Sun-Earth line. • A solar wind constellation that observes from ~ 30 RE upstream. • An ionospheric constellation to drive coupled magnetospheric-ionospheric models. • Fleet of 12U–27U 3-axis stabilized smallsats. • Active direct measurement (VHF-UHF Radio) of TEC. • Passive indirect measurements (UV) of TEC. • Low-frequency Imaging Array in Space
Earth Science	• UV/VIS/SWIR spectrometer, • microwave limb sounder, • TIR radiometer, geodesy, • cloud profiling radar, • ocean salinity, • precipitation, • ocean surface 3D wind speed, • Ka-band radar interferometer, • millimeter wave spectrometer
Astrophysics	• Synthetic aperture arrays for radioastronomy. • Self-assembled segmented telescopes in visible/IR/UV. • Radio-occultations



Swarm to Solar System Body Fractionated Constellation at Halley 2061

Science over number of instruments/platforms



number	Planetary science	Heliophysics	Earth Science	Astrophysics
A few	• Multiple TLS/QITMS spectrometers would collect and analyze elements at separate spatial locations and different times if on different orbits. • Multiple thermal imaging spectrometers would provide thermal data at separate spatial locations and different times if on different orbits. • Multiple Doppler imagers at separate spatial locations and different times on different orbits.	• DYNAMIC, MEDICI, IMAP, Geospace Dynamics Coupling (GDC) • Stereoscopic EUV imaging. • Magnetography well off the Sun-Earth line. • A solar wind constellation that observes from ~ 30 RE upstream. • An ionospheric constellation to drive coupled magnetospheric-ionospheric models. • Active/Passive direct measurement (VHF-UHF Radio, UV) of TEC. • Low-frequency Imaging Array in Space	• Stereo sounders/profilers • UV/VIS/SWIR spectrometer, • microwave limb sounder, • TIR radiometer, geodesy, • cloud profiling radar, • ocean salinity, • precipitation, • ocean surface 3D wind speed, • Ka-band radar interferometer, • millimeter wave spectrometer	• Gravitational Wave Surveyor • Gravitational Wave Mapper
~10	• CubeSats distributed across the rings of Saturn. • SmallSats sampling multiple comets as part of the same mission • Constellations will be useful to sample magnetic and plasma field at multiple locations. Would need >10 Cubesats. Sampling of many bodies within a population.	• Magnetospheric constellation tomography • Fleet of 12U–27U 3-axis stabilized smallsats	• CloudSat, GACM, GEO-CAPE, GPC-Core, HyspIRI	• Cosmic Dawn Mapper
~100	• 100's of asteroid mappers	• Large constellations	• Various Earth Imagers	• Radio interferometer

Summary

Domain	Science with smallsats	Constellations	Formations
Planetary Science	Established	Many possibilities	Not yet
Heliophysics	Established	Many possibilities	SunRISE
Earth Science	Established	There are already proposed / selected active missions that utilize small/cube sats. (flying) CYGNSS, (proposed/selected) TROPICS	Proposed D-TRAIN, SABLE, TEMPEST EV, smallsat GRACE. 3D Winds from passive approach
Astrophysics	Emerging	Radioastronomy (Optical/Radio-interferometry)	RELIC

- CubeSat/SmallSats and constellations are game-changers in terms of making certain measurements possible
- Future work: Quantification of science return vs. implementation and operation cost, risk, and complexity is been assessed via ongoing decadal-class science concepts and new ideas for the next Planetary Science, Heliophysics, Earth Science, and Astrophysics Decadal Surveys